Assessing Environmental Risks of Energy

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Introduction

The increased attention given by analysts, decision makers, and the public in recent years to the environmental impacts of energy production has not been an aberration or a fad; it is the natural consequence of a growing recognition that an increase in human well-being, rather than an increase in energy supply for its own sake, should govern society's energy choices. Since well-being is influenced by environmental conditions as much as by economic conditions, the wisdom of a given energy choice simply cannot be determined without systematic assessment of its environmental consequences. We offer here some brief observations about the nature and state-of-the-art of this assessment, as reflected in recent summaries and reviews.[1-8]

Discussion

No energy source presently known or imagined—including conservation, renewables, or fusion—is entirely free of environmental liabilities. The liabilities may be of many different kinds: direct impacts on public and occupational health and safety associated with accidents and effluents directly toxic to humans; direct damage to property and other economic goods and services; disruption of ecological and geophysical systems that perform services essential to human well-being; unwelcome change imposed on sociopolitical conditions and processes; or the imposition of psychological distress and aesthetic nuisances.

Unlike energy's economic benefits, these environmental liabilities, for the most part, do not lend themselves to single-measure (e.g., monetary) characterization. Some are resistant to quantification of any sort. Many are describable in part by quantitative indices, but the indices are incommensurable from one category of impacts to the next. In a few cases, conventions have been developed for monetizing the harm (e.g., the dollar "cost" of a human death, or days of illness, or lost recreational asset), but the unavoidable value judgments inherent in such conventions make them a continuing subject of dispute.

Analysts tend naturally to focus on the subsets of the environmental impacts that are easiest to quantify. In general, occupational impacts are more easily quantified than public impacts, injuries more easily quantified than illnesses, fatalities more easily quantified than nonfatal damages, early fatalities more easily quantified than delayed ones, and direct damages from accidents and effluents more easily quantified than the indirect damages caused by disruption of biogeophysical and sociopolitical conditions and processes. There is good reason to believe that the emphasis produced by this focus on quantification is almost exactly opposite to the real relative importance of the impacts.

What do we mean by "importance"? Part of it—"expected harm"—can be defined formally as the sum of all possible damages weighted by their probabilities.* Where the size of the possible damages and the probabilities of their occurrence are highly uncertain, as is often true for energy's environmental effects, it makes sense to give some weight to "worst cases"—that is, to ask how great the harm will be if the most pessimistic assessments turn out to be correct. Another determinant of the importance of an impact is the degree of associated maldistribution. Will those who make the energy choices and those who benefit from them bear the main environmental costs? Or will these costs be exported in space and time, beyond the decision makers and the beneficiaries, fostering both inequity and inefficiency?

But such criteria, the most important environmental liability of oil as an energy source is probably not air pollution or oil spills but the chance that war will be waged over access to the world's remaining supplies. The most important environmental liability of coal is not the occupational toll of mining or the public toll from coal-transport accidents (the most easily quantified impacts of coal), or the direct damage to public health from airborne sulfates (quantifiable in principle, but highly uncertain in present practice); rather it is the threat of global climate change posed by accumulating atmospheric carbon dioxide, the consequences of which (through disrupted agricultural productivity) are potentially enormous but highly resistant to convincing quantification. The most important environmental liability of nuclear fission is neither the routine nor accidental emissions of radioactivity, but the deliberate misuse of nuclear facilities and materials for acts of terrorism and war.

No single index, monetary or otherwise, can capture all the diverse attributes of environmental threats. This means

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*This definition begs the question of the units in which the damages are to be measured. Ordinarily, an expression for expected harm might contain separate terms for each different incommensurable *type* of harm, e.g., loss of life expectancy in person-years, person-days of illness, dollar value of destroyed property.

that comparing such threats from one energy source to the next, or even comparing different threats from a single energy source, is like comparing apples and oranges. Unavoidably the comparison involves personal values and preferences as well as technical judgment. This observation does not mean there is no role for analysis. The analyst's job is to illuminate the nature of the risks, in all their dimensions. Once analysts have described the threats as completely as they can, the decisions about which threats to accept, which ones to abate, and which ones to avoid are properly a *political* matter as is any other social choice where individual values and preferences conflict.

Assessments of the risks of energy options are relevant to two different kinds of decisions. For both kinds, the key issue is *relative* risks, but the bases of the comparisons and the kinds of information needed for the two types of decisions are somewhat different. One type of decision involves how to allocate efforts and resources for risk abatement. For example, how should resources to be spent on reducing the environmental costs of an energy source be allocated among that energy source's different forms of environmental damage? Or, how should risk-abatement efforts be allocated among *all* forms of energy supply? Or among all environmental risks, including nonenergy–related risks, to which workers and members of the public are exposed? The second type of decision involves comparing the environmental costs of alternative ways to obtain given energy benefits in the future, so that these costs can be weighed together with other criteria in deciding which energy systems to develop and use.

To be useful, a risk assessment for either purpose must specify its aim, define an appropriate basis of comparison, and choose, calculate, and present indices of harm in a manner consistent with the stated aim and comparative framework. In addition to these requirements, a risk assessment must—if it is to illuminate rather than obfuscate—avoid certain other pitfalls that have plagued this field: illusory precision, excessive aggregation, confusion of net and gross risks, and, as already emphasized, preoccupation with quantifiable risks to the exclusion of more important ones that resist quantification. In the following paragraphs, we elaborate briefly on some of these difficulties.[2,3,6,7,9]

Uninformative comparisons of the first kind: noncomparable energy benefits—Where the aim of risk assessment is to illuminate the characteristics of different energy systems, the most informative comparisons are among systems designed to obtain the same energy benefits in the same time frame. Thus it is useful to compare long-term electricity sources (fusion, fission fast breeder reactors, ocean thermal energy conversion) with one another and short-term sources of liquid fuel (imported oil, offshore domestic oil, alcohol from grain) with one another, but comparisons across time frames and energy forms should be avoided. It is of little use to know that energy source A is less risky environmentally than source B, if A will soon be exhausted and B is not yet available but eventually will be able to meet civilization's needs millennia. Comparing the risks of obtaining a gigajoule of electricity to the risks of obtaining a gigajoule of liquid fuel is not very informative either, because one cannot be transformed into the other without additional processing that entails further environmental impacts.

Uninformative comparisons of the second kind: energy vs nonenergy benefits—The literature often compares an environmental hazard of an energy source with other environmental hazards that have nothing to do with energy, such as the chance of being hit by a meteorite or the chance of being killed in an earthquake. Sometimes the intent of such comparisons is simply to put the magnitude of the energy risk into perspective by using a more familiar nonenergy risk as a point of reference (although the meteorite and the earthquake—both real examples—hardly qualify as familiar). Comparisons of energy and nonenergy risks have a second legitimate function, when their aim is to assign priorities, among all societal risks, for the allocation of risk abatement effort. Where this is the purpose, what matters is not the absolute size of the risks but rather the amount by which each risk can be reduced with a given expenditure of funds—a quite different index.

All too often, however, the explicit or implicit intent of comparisons of energy and nonenergy risks is to convey a message about the "acceptability" of the energy risk. For example, if Californians accept a risk of being killed in an earthquake, why should they not accept a much smaller risk of being killed in a nuclear-reactor accident? The fallacy in trying to judge acceptability in this way is that the benefits obtained along with the risks being compared are qualitatively different. Many people live knowingly with California's earthquake risk because they believe that in so doing they obtain a combination of benefits (climate, scenery, work opportunities, etc.) not obtainable in any other way. By contrast, the benefit of having nuclear reactors is simply electricity, which is obtainable in a number of other ways.

The most informative comparisons for nuclear power's risks are the risks of other ways to get electricity and the risks people accept from electricity at the point of end use.[3]

Inconsistent system boundaries—Where the intent of an environmental assessment is to identify the most hazardous subsystems associated with an energy source so that efforts at hazard abatement can be focused where they are most needed, it makes sense to analyze those subsystems (or fuel-cycle steps) one at a time—e.g., mining, fuel processing, fuel transport, conversion to electricity, etc. However, where the aim of the assessment is to tally up the total environmental costs associated with an energy source, or to compare the environmental costs of one energy source with another, it is essential that all the fuel-cycle steps and associated subsystems and activities be included for every energy source that is being considered. It is surprising how often this elementary principle of consistency has been neglected in published assessments. A striking example was the widely publicized risk comparison of renewable and nonrenewable energy sources by Inhaber[10] which included the occupational hazards of materials acquisition and facility construction in the risk totals for the renewable sources but omitted these hazards in the totals for the nonrenewables.[6] A less transparent example of the inconsistent-boundary syndrome is the much-cited calculation that a coal-burning power plant produces a greater radiation hazard than does a properly

operating light-water reactor,[11] owing to the coal plant's release up the stack of uranium and thorium present as trace contaminants in the fuel. This conclusion follows from drawing the system boundaries so that they include the main source of radionuclide emission in the coal fuel cycle (the power plant) but exclude the activities in the nuclear fuel cycle (mining, milling, reprocessing) that account for 90 per cent or more of the routine emissions caused by nuclear generation of electricity.[12]

Confusion of average and marginal risks—If the aim of an assessment is to determine the impact on society of past energy choices and associated activities up to the present, it is appropriate to work with the *average* effects of existing facilities and practices. If, on the other hand, the aim is to help determine what energy technologies should be developed and/or deployed in the future, one should assess the effects of new or projected facilities and practices—that is, one should look at the effects *at the margin*. Like consistency of system boundaries, this elementary dictum has often been ignored. For example, in comparisons of coal and nuclear power, where the evident intent was to illuminate the consequences of alternative choices for future electricity generation, it has been commonplace to compare the operation of modern nuclear facilities with the operation of older coal facilities using equipment, conditions, and practices that would not be tolerated in new ones. The environmental effects of new coal mines and power plants, meeting present mining regulations and new source performance standards, are much smaller than the effects averaged over all existing facilities.[13]

Confusion of net and gross risks—If either assessment of the absolute level of hazard of one energy option or comparison of the hazards of more than one option is to be useful, the assessment should attribute to an energy option only the *net* risks that this option induces—that is, that part of the total risk to society that would not have existed had the option not been chosen. The occupational hazards associated with constructing a power plant are an example of gross as opposed to net risks. The net risk in this case is the difference between the occupational hazards of constructing the power plant and the occupational hazards to which the workers would have been exposed had they been doing something else (including being unemployed, which itself is not without risk). Since it is hard to know in practice exactly what workers in the energy industry would be doing if not working on energy, probably the most reasonable procedure is to subtract from the gross risk per worker the average occupational risk per worker in the whole economy. After all, if the jobs involved with an energy source are not more hazardous *per job* than the national average for all employment, it seems unreasonable to attribute to that energy source a measure of risk that is really only measuring labor intensity. Futhermore, in a high-unemployment economy, it may be argued that a high labor requirement per unit of energy output is an asset in an energy source, rather than a liability.

Illusory precision—Perhaps the most striking and pervasive shortcoming in the literature of energy hazards is insufficient attention to the magnitudes of the variations and uncertainties associated with the "best estimates" or "central values" supplied. *Variations* refer to differences that arise from known and predictable differences in conditions (e.g., different pollution-control technologies, different fuel compositions, different sites). *Uncertainties* refer to results based upon insufficient knowledge about the performance of even a completely specified technology and/or about the environmental consequences that will follow from that performance. In part, these uncertainties derive from stochastic aspects of the performance of technology and of environmental conditions and processes, and in part they derive from the necessarily statistical character of the evidence on such environmental impacts as pollution-caused disease. For information about environmental hazards to be useful to policy analysts, decision makers, and the public, it must specify variations and uncertainties along with mean values. The variations, and the basis for them, reveal something about the range within which certain choices can affect outcomes. The uncertainties represent *a part of the burden* imposed on society by the use of a given energy source, which the public and their decision makers must take into account in choosing which energy sources to use. A principle long recognized in formal benefit-cost analysis is that the uncertainty surrounding a mean value must be counted as a cost beyond that associated with the mean value itself.

The rampant illusory precision in the literature of energy risks includes frequent reporting, to two and three significant figures, with no statement of uncertainty bands, of estimates of public disease from oxides of sulfur and expected public deaths from reactor accidents, for which the real uncertainty ranges span two to four orders of magnitude or more.[9] Such illusory precision becomes doubly misleading when it serves as the basis for rank-orderings of different energy technologies according to (for example) direct threats to human health and safety: not only are the uncertainties often large compared to the differences in mean values on which the rankings are based, but the unwary user is likely to think that presentation of such a ranking implies inclusion of all the important contributors to the risk, which is rarely the case.

Excessive aggregation—One form of excessive aggregation is the averaging, into one mean value, of a range of environmental characteristics corresponding to different facility types, different facility sizes, different management practices, and different geographic locations, as discussed earlier under "illusory precision". The combination of dissimilar risks into a single index of hazard, such as the combining of occupational and public risks, is another form of inappropriate aggregation. The occupational-public example of risk aggregation tends to mix net risks with gross risks (as discussed earlier), as well as concealing important differences in the extent to which such risks are suffered voluntarily, internalized economically, and hence perceived socially. More subtle forms of over-aggregation also abound. One is the widespread tendency to tally up total numbers of public or occupational deaths without regard to the greatly differing loss of life expectancy that different causes of death entail. For example, a death due to aggravation of preexisting respiratory disease in an air pollution episode may

claim only weeks to months of the victim's life, while a typical cancer might claim 10 to 30 years and a typical accidental death perhaps 20 to 40 years.

Hidden values—As already emphasized, choices among alternatives characterized by numerous noncomparable attributes cannot be made without the introduction of tastes and values. Whether you prefer three apples or three oranges is a matter of taste. Whether you prefer three days in jail or a $300 fine depends on whether you value time or money more. Whether you prefer an energy source that increases slightly the chance of nuclear war or one that poisons one in 10,000 of its users is equally a value judgment. These choices are not the province of analysts; they belong properly to the public and the political process. But many analysts and analyses tend to make them for us, intentionally or unintentionally, by omitting from comparisons of alternatives those classes of risks that the *analyst* has decided are uninteresting, too hard to quantify, too speculative, or too likely to be "misinterpreted". Such omissions hide the analyst's values in the way the choices are presented, thus biasing the outcomes.

Conclusion

Considering the difficulties in assessment practice and the shortcomings in available data, what can be said about the relative risks to human health and safety posed by energy sources? Based on the thinking summarized here and reviews of data summarized elsewhere,[2,3] we venture the following conclusions.

First, the most easily estimated impacts—the occupational hazards of building and operating energy systems—fall for the most part within a rather narrow range for both conventional and renewable sources of energy. Those energy systems with very large materials requirements (for construction of the facilities or for fuel) tend to fall at the high end of this range, but it should be noted that the very high demands for construction materials attributed to certain renewable energy sources in some studies would, if they were correct, ensure on economic grounds alone that these particular systems would never be built commercially. The occupational hazards for economically realistic energy systems investigated so far, while valid cause for worker concern and the expenditure of greater efforts at abatement, do not vary enough from one energy source to the next to provide a major basis for choosing one source over another. This conclusion is made all the more robust by three circumstances: the *net* occupational hazards are smaller than the gross ones usually tabulated; these hazards *are* generally susceptible to reduction by identifiable technical and managerial measures; and the people exposed to the risks are compensated for the hazards, at least partially, by the wages and benefits they receive.

Certain new energy systems, however, may entail special occupational hazards that cannot be evaluated at present. In particular, the hazards associated with launching, constructing, operating, and maintaining orbiting solar power stations could be extremely high. Similarly, the production of synthetic fuels from biomass and from unconventional fossil fuels such as oil shale and tar sands, and the production of photovoltaics using processes involving particularly toxic substances, might result in larger occupational impacts than other energy sources. These possibilities warrant continued attention.

Direct threats to public health and safety are considerably more difficult to evaluate, but it is clear that there are some hazards of high potential significance that remain resistant to convincing quantification and resistant to remedy. Threats to public health from the routine emission of air pollutants from combustion, for example, are highly uncertain but potentially severe. Among the major air pollutants, only sulfur oxides in the presence of particles can be associated at present with a quantitative dose-response relation, and even in this case the uncertainty is enormous—a range spanning at least four orders of magnitude if the index is person-years of life expectancy lost. Public health threats from nitrogen oxides, particulates, organic hydrocarbons, and other compounds are not presently quantifiable but deserve the closest continuing attention. Similarly, the health effects of the whole array of energy-related water pollutants need to be much more carefully investigated.

Finally, the *indirect* public health and safety effects of energy systems are the most poorly quantified to date, the most difficult to quantify in principle, and potentially the most serious. The greatest indirect risks appear to be associated with conventional energy options. Effects on climate from the atmospheric increase in carbon dioxide caused by the combustion of fossil fuels; the effects on environmental and economic goods and services caused by acid precipitation from fuel combustion; the risk of nuclear terrorism arising from national or subnational groups gaining access to nuclear materials from commercial nuclear power facilities; and the risk of war over access to oil and other energy resources, all fall into the category of indirect effects that are resistant to convincing analysis but possibly enormously destructive. By contrast, the greatest asset of certain of the renewable energy options may be their lack of large, indirect environmental threats together with their tendency to impose their main environmental burdens on those receiving the energy benefits. These advantages may well prove to be persuasive to those involved in choosing among our energy options.

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Prospectives on the Risks of Alternative Fuel Cycles

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Abstract: A commentary is provided on the uncertainties in the data and in qualifying the phenomena relating to the risks imposed by the various steps involved in the use of coal, oil, natural gas, hydropower, and nuclear fuels for the generation of electricity. Uncertainties appear to be extremely large for hydropower which exhibits both large scale ecological impacts and the potential for high consequence, moderate frequency events at specific sites. Major risk-related uncertainties with the use of nuclear fuels include those surrounding nuclear weapons proliferation and reactor accident frequencies and consequences. Uncertainties for coal and oil include specification of the damage function of air transported sulfates and the effects of atmospheric CO_2 buildup, acid rain, and groundwater contamination from mine water runoff. Compounding these problems is the potential impact of the growing global competition for a diminishing supply of oil. In the studies reviewed herein, the assessed risks of the nuclear fuel cycle are no greater than those of the primary alternatives. Prudence suggests that we do not totally reject any particular option at this time on the basis of health effects alone; similarly, no option is an undisputed choice. (*Am J Public Health* 1981;71:1050–1057.)

Introduction

The generation of electrical energy has become an integral part of our society, resulting in both positive and negative impacts. Because of changing resources, our energy options are in a state of evolution. An essential ingredient in the formulation of responsible policy regarding the choice of an energy option is an identification and quantification of that option's impact.

A partial measure of the negative impact of technical endeavors such as energy generation is the estimate of health risks. Although formal definitions of risk have been made,[1–3] it is convenient here to be fairly general in its definition. The measure of risk may be based on actuarial data (e.g., the number of people killed annually in automobile accidents) or it may be based on calculation using a model (e.g., the potential restriction of land use due to a nuclear reactor accident). The use of such measures of negative impact is complicated by uncertainties and inaccuracies in the data or models as well as the inability to quantify certain phenomena (e.g., effects of acid rain). In this paper, some sources of uncertainty in the estimates of health effects of energy generation technologies are discussed.

The current literature assessing the risks of conventional fossil fuel-electric, hydroelectric, and conventional nucle-

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